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RECENT CHANNEL ADJUSTMENTS IN ALLUVIAL RIVERS OF TUSCANY, CENTRAL ITALY

MASSIMO RINALDI*

Department of Civil Engineering, University of Florence, Via S.Marta 3, 50139 Florence, Italy

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ABSTRACT

Drastic channel adjustments have affected the main alluvial rivers of Tuscany (central Italy) during the 20th century. Bed-level adjustments were identified both by comparing available topographic longitudinal profiles of different years and through field observations. Changes in channel width were investigated by comparing available aerial photographs (1954 and 1993–98).

Bed incision represents the dominant type of vertical adjustment, and is generalized along all the fluvial systems investigated. The Arno River system is the most affected by bed-level lowering (up to 9 m), whereas lower incision (generally less than 2 m) is observed along the rivers of the southern part of the region. Human disturbances appear to be the dominant factors of adjustments: the main phase of vertical change occurred during the period 1945–80, in concomitance with the phase of maximum sediment mining activity at the regional scale.

The second dominant type of adjustment that involved most of the rivers in the region consists of a narrowing of the active channel. Based on measurements of channel width conducted on aerial photographs, 38% of the reaches analysed experienced a narrowing greater than 50% of the initial channel width. The largest values of channel narrowing were observed along initially braided or sinuous with alternate bars morphologies in the southern portion of the region.

A regional scheme of channel adjustments is derived, based on initial channel morphology and on the amounts of incision and narrowing. Different styles of channel adjustments are described. Rivers that were originally sinuous with alternate bars to braided generally became adjusted by a moderate incision and a moderate to intense narrowing; in contrast, sinuous-meandering channels mainly adjusted vertically, with a minor amount of narrowing. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS: channel adjustments; incision; channel narrowing; human disturbances; Tuscany; Italy

INTRODUCTION

Channel adjustments due to vertical and lateral instability along alluvial rivers, often induced by various types of human disturbance, may become unacceptable for the human activity itself when the alluvial plain adjacent to the river is densely populated and developed. Channel incision and related adjustments of channel geometry may have several environmental and societal effects (Bravard *et al.*, 1999), such as: damage to bridges, artificial levees and other engineering structures; loss of agricultural lands; delivery of large volumes of sediments and/or woody debris and associated effects on inundation hazards; damage to aquatic and riparian ecosystems; loss of habitat diversity, of spawning gravel for fish and impoverishment of the fish community; effects on river–water table relationships, inducing loss of alluvial groundwater storage and damage to riparian vegetation. The management and stabilization of unstable rivers pose several problems to river engineers and managers, and the importance of the geomorphological approach, accounting for channel morphology and dynamics, in providing useful guidance for stabilization schemes is increasingly recognized (Thorne, 1998; Darby and Simon, 1999).

Throughout Europe, large alluvial rivers have experienced a long history of human modification, and historical channel changes of many of them have been documented (Petts *et al.*, 1989). Numerous studies have shown similar trends of channel adjustments, with a previous historical period, extending to the start of

* Correspondence to: M. Rinaldi, Department of Civil Engineering, University of Florence, Via S.Marta 3, 50139 Florence, Italy.
E-mail: mrinaldi@dicea.unifi.it

the 19th century, characterized by aggradational processes affecting the different components of the fluvial system (alluvial plain, channel bed, delta), followed by an inversion of the general aggradational trend during the 19th and 20th centuries as a result of different types of human disturbance (Petts *et al.*, 1989; Lajczak, 1995; Bravard *et al.*, 1997; Winterbottom, 2000). Most recent studies (Knox, 1983; Macklin and Lewin, 1989; Rumsby and Macklin, 1994; Macklin *et al.*, 1998) have demonstrated that climatically driven variations in flood frequency and magnitude can have an important role in controlling vertical and lateral instability.

Incision and narrowing have often been indicated as the two dominant types of channel adjustment that have occurred during the 20th century. Studies on different rivers in France generally describe a progressive decrease in bed-load supply during the 20th century due to land-use changes and induced bed degradation and/or channel narrowing (Marston *et al.*, 1995; Bravard *et al.*, 1997; Liebault and Piegay, 2001, 2002). A recent study on rivers in Scotland (Winterbottom, 2000) has also shown generalized incision and a decrease in mean channel widths between 1971 and 1998.

In Italy, previous studies have mainly concentrated on planimetric variations and human impact on alluvial rivers (Castiglioni and Pellegrini, 1981; Braga and Gervasoni, 1989; Canuti *et al.*, 1994; Castaldini and Piacente, 1995). Subsequently, a series of studies has focused on bed-level adjustments of the Arno River and their temporal trends (Rinaldi *et al.*, 1997; Billi and Rinaldi, 1997; Rinaldi and Simon, 1998; Agnelli *et al.*, 1998), showing an intense channel incision during the last 150 years induced by a combination of human disturbances, including upstream sediment retention by weirs along tributaries, dams, and alluvial sediment mining. Surian (1999) has recently documented a significant channel narrowing and reduction of braiding combined with a moderate bed incision along the Piave River, northeastern Italy, mainly as result of flow regulation and embankments. Other studies conducted along rivers of the upper Po Plain (Maraga, 1989) and along the Trigno River (Aucelli and Rosskopf, 2000), on the Adriatic slope of the Central Apennines, have clearly shown that channel narrowing has represented an important type of adjustment during the recent decades, with frequent modification from braided to single-thread channel morphologies. Most of the studies of morphological adjustments during the 20th century in alluvial rivers of Italy agree in considering the role of natural factors as being very limited compared with the large human impact (in particular, sediment mining), indicated as the dominant cause of instability (Surian and Rinaldi, 2003).

In Tuscany, central Italy, many rivers have experienced severe vertical instability and width adjustments during the 20th century. Although channel incision was already known for the Arno River and for its main tributary, the Sieve River, the extension at regional scale of vertical adjustments and the type and amount of width adjustments were not investigated in detail. The other fluvial systems of the region present a wider variety of channel morphologies than those observed along the main alluvial rivers of the Arno River system, as well as a minor degree of human disturbances and control on channel form. For this reason, the present study starts from a basic description of the channel morphologies observed in the region, to allow a better comprehension of their adjustments, and subsequently a regional classification scheme based on adjustment processes is proposed. For river management and restoration, the need to develop schemes of classification based on dynamic adjustments (i.e. Brookes, 1988; Simon, 1989; Downs, 1995) rather than only on channel forms is increasingly being recognized (Thorne, 1997; Doyle *et al.*, 2000).

The overall objective of this paper is to report a case study describing the different types and amounts of channel adjustments at a regional scale that have occurred during 20th century in rivers with various morphologies and human disturbances. The specific purposes are to: (a) analyse the types of response and style of adjustments of rivers with different initial channel morphology; (b) develop a regional classification scheme based on trends of channel adjustments; (c) compare the trends of adjustments with channel evolution observed in other fluvial systems characterized by different physical conditions and human disturbances.

STUDY AREA

The study area coincides with Tuscany (22 991 km²), a region of central Italy, delimited by the Northern Apennines on the northeastern side and by the Tyrrhenian Sea to the west (Figure 1). Tectonic evolution has established a morphology characterized by aligned ridges with an NW–SE trend, made up of Mesozoic and Tertiary units with folded structures, separated by basins with a similar trend. Consequently, the fluvial

network of the region derives from a relatively recent drainage evolution strongly influenced by extensional tectonics, with a prevalence of streams with an NW–SE trend, following the orientation of the main grabens (Figure 1A; Bossio *et al.*, 1992).

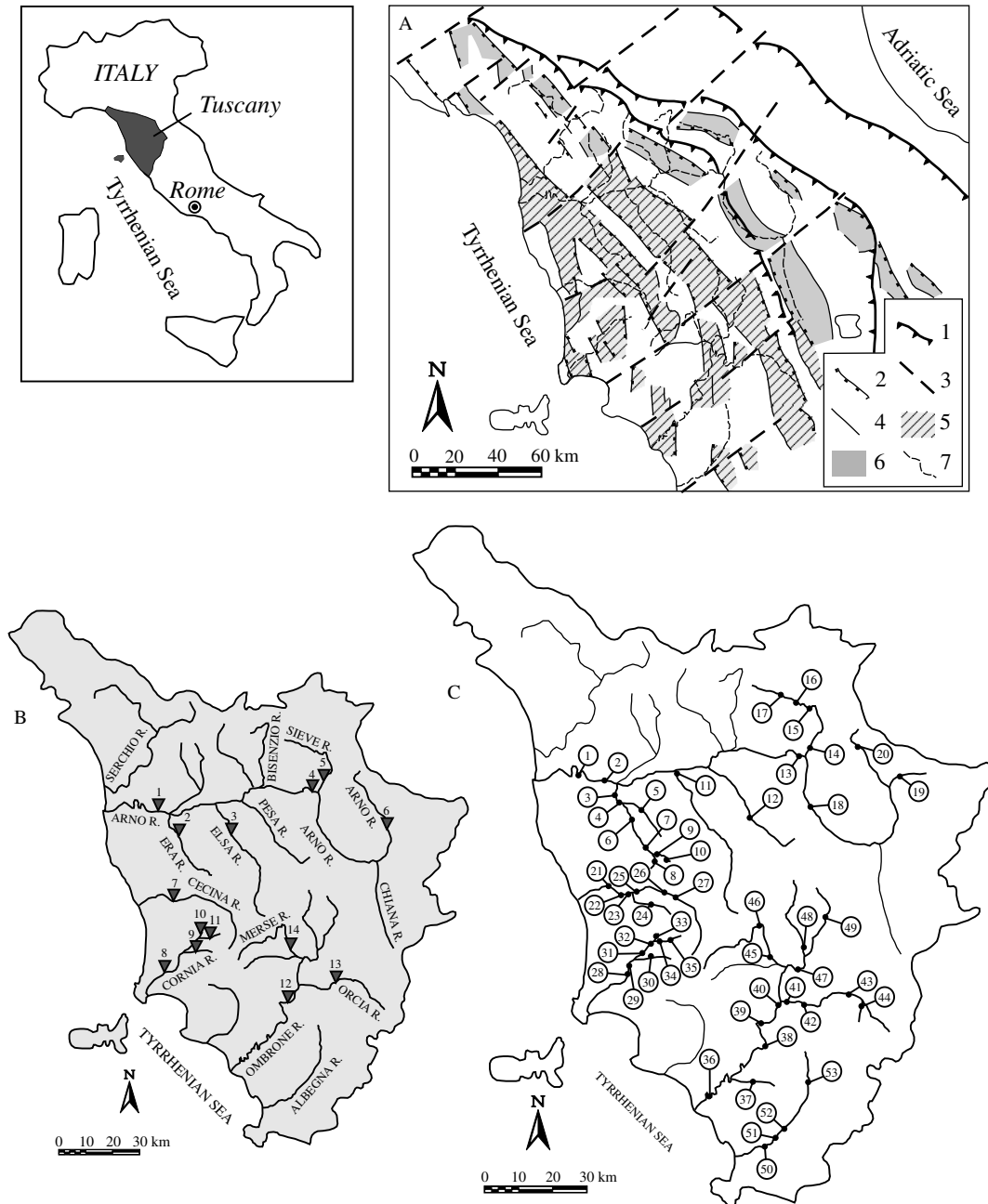


Figure 1. Study area location and selected sites. (A) Physiographic sketch of the region showing the Neogene marine and fluvio-lacustrine basins and the main tectonic features (reproduced with permission of the Director of Dipartimento di Scienze della Terra, modified from Bossio *et al.* (1992)); (1) main overthrusts; (2) main faults bordering the basins; (3) transverse tectonic lines; (4) minor faults bordering the basins; (5) marine basins; (6) fluvio-lacustrine basins; (7) main rivers. (B) Main rivers and main gauging stations of the region. (C) Location of selected sites

The main watersheds of the region are those of the Arno River (area of 8830 km²), Ombrone River (3500 km²), and Serchio River (1435 km²), followed by the Cecina (900 km²), Albegna (749 km²), and Cornia (419 km²) rivers, these last three being located in the southern part of the region. The main rivers of the region, in their upper and middle courses, are typically composed of reaches cut into the unconsolidated marine or fluvio-lacustrine sediments alternating with narrow bedrock-controlled reaches, whereas in their terminal reach they flow through relatively wide alluvial coastal plains (Rinaldi, 1995).

The central and southern part of Tuscany falls within a temperate climatic zone with a dry season, the Mediterranean climate category, and the northern portion has some continental climate characteristics. The principal morphometric, climatic, and hydrologic data for the main gauging stations with sufficiently long time-series of discharge data are reported in Table I.

HUMAN DISTURBANCES

Human impact represents a primary factor in the historical evolution of the fluvial systems of Tuscany. During past centuries, many interventions at basin level were undertaken, including deforestation and large-scale changes in land use. Furthermore, the main alluvial river reaches have been subject to numerous in-channel engineering works, mainly including bank protection (groins, dikes, revetments, walls), straightening (including artificial meander cutoffs), resectioning, diversions (as part of flood-control systems), weirs, and artificial levees (to prevent flooding of urban areas). Notwithstanding this extensive control exerted by man, flood plain, in-channel deposition, and growth of the delta of the main rivers proceeded until the second half of the 19th century (Rinaldi and Rodolfi, 1995; Billi and Rinaldi, 1997).

River dynamics during the 20th century may have been affected by the following main categories of human disturbance:

1. Disturbances at basin level, concentrated between the end of the 19th century and the first decades of the 20th century, including reforestation of large upland areas favoured by a series of land management laws, stabilization of slopes, and construction of a large number of weirs along mountain streams (more than 2700 weirs were built in the Arno River basin).

Table I. Morphometric, climatic, and hydrologic data for the main gauging stations of Tuscan rivers (locations of the gauging stations are shown in Figure 1B)^a

River and flow gauging station	<i>A</i> (km ²)	<i>L</i> (km)	<i>H</i> (m a.s.l.)	ΔH (m)	<i>R</i> (mm)	q_{mean} (m ³ s ⁻¹)	Q_2 (m ³ s ⁻¹)
Arno (1)	8186	198	330	1650	1031	97.4	1203.8
Era (2)	355	37	225	650	1074	9.25	103.3
Elsa (3)	806	53	243	677	857	5.38	158.9
Arno (4)	4083	113	450	1585	1038	56.7	1186.0
Sieve (5)	831	58	490	1565	1213	15.7	410.7
Arno (6)	738	45	720	1407	1288	18.5	505.8
Cecina (7)	634	53	309	1018	944	7.61	339.9
Cornia (8)	356	40	252	908	941	2.98	361.1
Milia (9)	77	24	390	815	934	0.40	45.8
Massera (10)	58	13	222	485	861	0.50	97.2
Cornia (11)	97	19	338	785	953	0.69	51.4
Ombrone (12)	2657	80	346	1679	916	26.7	768.0
Orcia (13)	580	34	445	988	826	4.45	260.7
Merse (14)	483	54	365	911	1011	6.38	306.2

^a *A*: drainage area; *L*: river length; *H*: average basin elevation; ΔH : difference between higher and lower basin elevation; *R*: average annual runoff; q_{mean} : average of mean-daily discharges; Q_2 : peak discharge with 2 year return period.

2. Sediment mining. During the three decades after World War II the volume of bed material extracted from the alluvial rivers of the region increased by several orders of magnitude, initially as a consequence of the post-war reconstruction, and later as a result of rapid industrialization and urbanization.
3. Dams. This type of factor is limited, among the rivers considered in this study, to two dams constructed in 1957 along the upper course of the Arno River (location is shown in Figure 4).
4. Bank protection and levee construction. This type of disturbance has continued during the 20th century and has mainly affected rivers crossing the most intensely urbanized areas (in particular the Arno River and tributaries), whereas it is generally limited in rivers of southern Tuscany.

DATA COLLECTION AND METHODS

Channel characteristics

Numerous field visits along the main alluvial rivers and observation of aerial photographs were conducted prior to and during the entire period of study, allowing for an initial identification and description of the various river morphologies of the region.

A series of 53 representative reaches was selected on the basis of the previous phase, where more detailed observations and measurements of channel geometry were conducted. Rivers with a high degree of artificial control on natural form and processes were excluded from this phase of the research.

Field data collection in these selected sites consisted of the survey of a representative cross-section and the mean channel gradient. Bankfull elevation was identified based on field evidence, after Williams (1978). In the case of incised channels, bankfull was identified on the basis of a combination of morphological (presence of a new floodplain), vegetational (presence of mature woody vegetation), and sedimentary evidence. Topographic surveying was carried out on the whole channel cross-section delimited by the lower terraces adjacent to the bankfull channel.

A sediment sample was collected for each site. For most of them (48), consisting of gravel-bed rivers with exposed bars, the bar surface was sampled by the grid method (Wolman, 1954), using a half-phi template and a visual grain comparator for grains smaller than 8 mm (Billi and Paris, 1992). For the remaining five sites (site numbers 1 to 5), due to the lack of bars, it was not possible to use the same method; therefore, a bulk (volumetric) sample was collected from the river bed.

Channel planform sinuosity was measured from the most recent topographic maps available (at scales of 1:5000 or 1:10 000; period 1979–98), considering a channel length of approximately 50 to 100 times the channel width. For each site, channel-geometry parameters were obtained from the cross-section. A representative discharge with a return period of 2 years (Q_2) was then assigned to each selected reach using one of the following two criteria: (a) for sites along rivers with a gauging station, statistical frequency analysis of annual peak discharges was conducted, and the value of Q_2 was scaled by the drainage area; (b) for sites along rivers without a gauging station, the representative discharge was calculated using the regional flood frequency analysis of Tuscany (Regione Toscana, 1998).

Channel adjustments

Bed-level adjustments were identified and estimated by: (a) available data on topographic profiles; (b) specific gauge analysis (Blench, 1973) for existing gauging stations; and/or (c) field evidence of channel incision or aggradation (Simon, 1989; Sear *et al.*, 1995; Thorne, 1998), combined with information gathered from residents.

The historical series of topographic profiles (including the years 1844, 1935–36, 1950–54, 1978–80, 1987–90), available for the Arno and Sieve Rivers, have already been reported elsewhere (e.g. Rinaldi and Rodolfi, 1995; Rinaldi and Simon, 1998; Agnelli *et al.*, 1998) and provide an accurate reconstruction of the bed-level changes along these two rivers.

Field evidence included: (a) exposure of bridge piles or other hydraulic structures; (b) characteristic morphological features and associated riparian vegetation of incised channels (Simon, 1989; Darby and Simon, 1999), such as a relatively large distance between the lowermost limit of woody vegetation and mean low-water level, relatively high and steep banks, widespread exposure of roots; (c) presence of low terraces close

to the channel. In the latter case, the difference in level between a terrace identified as being a floodplain from the aerial photographs of 1954 and the present active floodplain was used to gain an approximate evaluation of the amount of incision. These types of geomorphological evidence were not limited to the 53 representative sites, but were extended by extensive field reconnaissance to the entire alluvial reaches of the rivers being studied in order to obtain a general reconstruction of the spatial distribution and extent of vertical adjustments. Planimetric variations and width adjustments were studied by comparing available aerial photographs. In particular, the following aerial flights were considered:

- (a) first aerial flight of 1954 (Volo GAI, Istituto Geografico Militare) covering the entire region and representative of the situation prior to the main phase of channel incision;
- (b) last available survey, taken in the period between 1993–98 (Regione Toscana).

In both surveys the aerial photographs are in black and white and have a scale ranging from 1:30 000 to 1:33 000. For a limited number of sites (ten), an orthophoto map from 1977–78 at the scale of 1:10 000 was also available.

An initial comparison of aerial photographs for each site was conducted to assess qualitatively the presence and type of channel changes and width adjustments. From these preliminary observations, significant changes in channel width were noted in many cases, so that, notwithstanding the relatively large scale of the aerial photographs, it was decided to estimate channel width differences quantitatively.

Limitations and errors in using aerial photographs and topographic surveys for measuring channel changes have been discussed in many previous papers, including those by Lawler (1993), Milton *et al.* (1995), Downward (1995). In particular, three main sources of error have been considered here, as in the recent work of Liebault and Piegay (2001): (a) optical deformation of the photograph; (b) errors due to limited perception of the naked eye; (c) possible errors due to banks hidden by overhanging riparian vegetation.

In the cases studied, a first selection of the rivers was based on the channel size. Relatively small streams (channel width less than approximately 25 m) were excluded from the analysis because of their limited size on the aerial photographs and the related problems of limited perception. For the rivers included in the analysis (a total of 42 sites out of 53), the first step consisted in the identification of the active (bank-full) channel limits. The active channel bed includes active bars (gravel surfaces, mostly unvegetated or with sparse, mainly non-woody vegetation) and the low-water flow channel. A stereoscope was utilized for identifying the active channel and separating it from the adjacent floodplain or terrace. Aerial photographs were then scanned (resolution of 1200 dpi) to allow for an enlargement of the images. The scale of the images was determined by locating a series of control points adjacent to the river (road junctions, houses, field boundaries) on available topographic maps at a scale of 1:10 000 (Carta Tecnica Regionale, Regione Toscana, period 1979–98). Subsequently, channel widths were measured, for the two different years, for the same channel length (of approximately 50 channel widths) by dividing it into ten parts and measuring a width for each one, and then assuming that the mean value is representative of the channel width of the reach. The same procedure was used for the orthophoto maps of 1977–78 available for ten of the sites.

An assessment of the three sources of error has been made as in Liebault and Piegay (2001): (a) the optical deformation error of the aerial photographs was estimated at about 3.5%, measured as a coefficient of variation of four scale measurements on the four directions of the image for a series of photographs; (b) perception error has been calculated as half of the smallest measurable dimension (considered as 0.25 mm and corresponding to a maximum of 4 m for the given scale of the aerial photographs) for each channel side, for a total of 8 m; (c) a 5 m error due to banks hidden by overhanging riparian vegetation has been assumed. Based on these estimations, values ranging from 14.1 m to a maximum of 22.4 m (depending on the size of the channel and subsequently on the resulting optical deformation error) have been considered as the limit above which measured differences in channel width can be considered significant.

Notwithstanding the previously discussed limitations and the relatively high margins of error, this procedure was able to assess a certain difference in channel width for 29 of the 42 sites analysed.

RESULTS

Channel morphologies

Rivers in the region form a continuum of channel patterns, mostly single-thread channels with a mixture of straight, sinuous and meandering planforms, whereas transitional morphologies between sinuous and braided are less common. The main channel morphologies are summarized in Figure 2. They are derived by taking into account more general classifications (e.g. Kellerhals *et al.*, 1976; Schumm, 1977; Brice, 1984; Rosgen, 1994; Alabyan and Chalov, 1998), in particular the classification schemes proposed by Schumm (1985) and Church (1992), and are strictly limited to the range of channel patterns observed in Tuscany. The regional classification scheme of Figure 2 is exclusively based on channel planform, and is applied to present channel types (observed from aerial photographs of 1993–98 and during the field reconnaissance) and to prior channel morphologies observed from aerial photographs of 1954.

The various channel morphologies are grouped into four general types of alluvial channel, here indicated as: (1) sinuous; (2) meandering; (3) sinuous with alternate bars; (4) braided.

Sinuous channels are characterized by variable sinuosity (sinuosity index 1.2–1.5) and include almost straight channels with a substantial absence of bars, or more sinuous channels with sporadic to frequent side

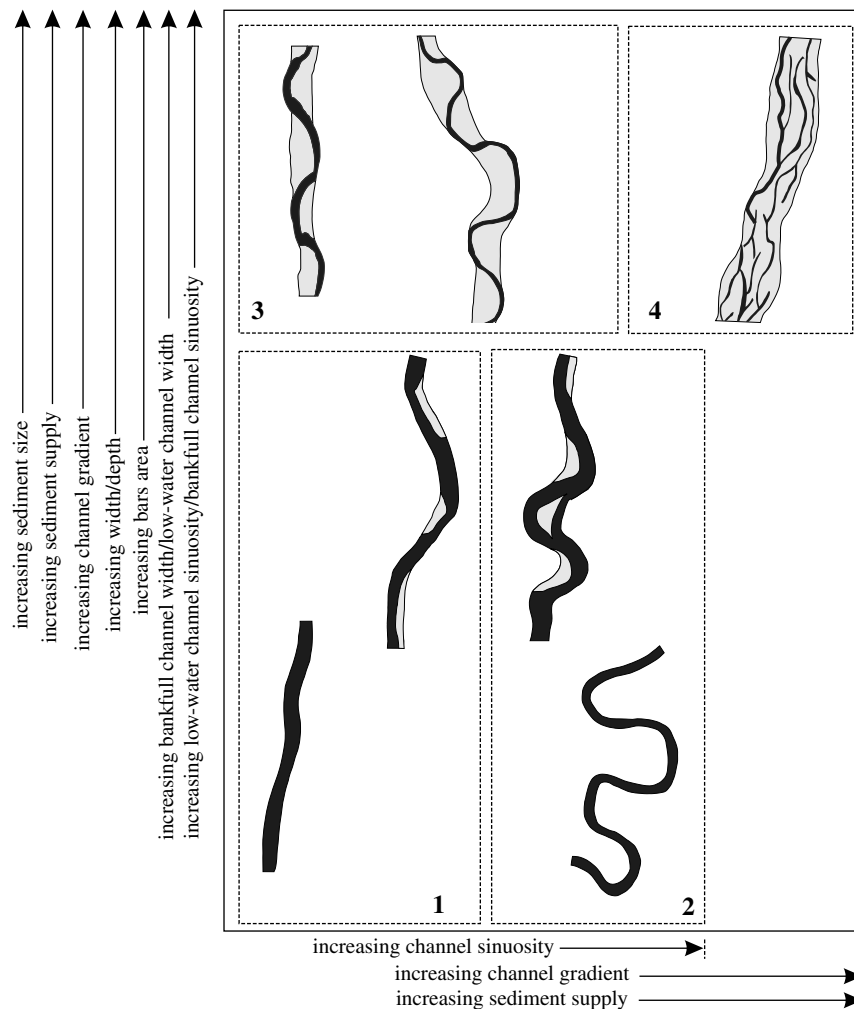


Figure 2. Channel morphologies observed in Tuscany; (1) sinuous; (2) meandering; (3) sinuous with alternate bars; (4) braided. In grey are indicated the active channel bars, in black the low-water channel

bars. Meandering channels are characterized by a higher sinuosity (1.5–2.5), lower channel gradients, and significantly finer bed sediment. This type of channel prevails along the coastal plains of the main rivers of the region, the Arno and the Ombrone, which are distinct from freely meandering rivers, since they mostly follow a general planimetric course inherited from their historical pattern (Reggiannini, 1998), with bank retreat and meander migration at present partially or totally prevented by bank stabilization works.

Sinuuous channels with alternate bars are frequent in the southern part of Tuscany, and are characterized by the following main features: (a) the presence of continuous, regularly alternating side bars occupying a relatively high percentage of the bankfull channel; (b) a significant difference in size and planimetric pattern between low-water and bankfull channel, with a narrow and highly sinuous low-water channel flowing within a much larger channel at formative (bankfull) flow, the latter having a planimetric course with low to medium sinuosity (index 1.1–1.45).

Similar channel morphologies have been developed in sand-bed flume studies and reported in Hickin's model (Hickin, 1969) and Keller's five-stage meander model (Keller, 1972), as well as being observed in natural straight channels in coarse-grained sediment (Lewin, 1976). Rivers of the Northern Apennines with these characteristics have also been indicated as 'wandering' by other authors (Billi, 1988) or, more recently, as 'pseudomeandering' (Teruggi and Billi, 1998; Bartholdy and Billi, 2001).

Braided channels have been observed for some rivers on 1954 aerial photographs, but they are uncommon at present, with local braiding phenomena observed only along some reaches of sinuous channels with alternate bars. In Figure 3, the main parameters regarding present channel geometry and bed sediment size for the 53 representative sites are reported, with the aim of more accurately characterizing the four categories previously defined on the basis of their morphological features and hydraulic properties. No attempts have been made to compare the data with existing empirical equations of channel geometry, neither to obtain regional regime equations nor discriminant functions between different morphologies, because it was not within the scope of this paper and because many of the rivers are out of equilibrium and in a process of transition in response to severely altered conditions.

Figure 3A shows that the data for bankfull width versus biennial discharge can be grouped into two broad categories (approximately separated by the dotted line in the figure), sinuous–meandering and sinuous with alternate bars–locally braided, even though abrupt limits are not well defined and some superimposition occurs. The more suitable parameter to discriminate the two broad channel categories is the width-to-depth ratio. In Figure 3B, the data of the two morphologies are well separated by the line corresponding to a width-to-depth ratio of 30, with sinuous–meandering rivers and sinuous with alternate bars–locally braided reaches characterized by width-to-depth ratios below and above 30 respectively.

Unit stream power is extremely variable for all categories (Figure 3C), ranging from 25 to 1000 W m⁻², with meandering channels having the lower values (less than 250 W m⁻²). Figure 3D shows that the data for median diameter of sediments and channel gradients are extremely scattered for the various channel morphologies. Only the data of meandering channels occupy a well-defined area of the diagram and are well distinguishable from the other morphologies, with an upper limit of channel gradient of 0.001 65 and an upper limit of median sediment size of 10 mm.

Channel adjustments

The spatial distribution of the vertical adjustments is summarized in Figure 4, where the rivers of the region being studied are divided into three qualitative classes of vertical changes (absent or limited incision, moderate incision, intense incision), based on the field evidence collected during the extensive field reconnaissance and, in particular, on the difference in level between the lower terrace and the present floodplain. Only for the cases of the Arno and Sieve Rivers does the classification provide a quantitative measure of vertical change, this being based on a comparison of the topographic profiles. For such cases, absent or limited incision corresponds to a bed lowering of less than 0.5 m; moderate incision corresponds to a bed lowering of less than 2 m; and intense incision corresponds to a bed lowering of more than 2 m.

Notwithstanding these limitations, it is well evident that incision is the dominant type of vertical adjustment and that it is generalized along all fluvial systems investigated. The largest incision is certainly that one documented along the middle and lower reaches of the Arno River (downstream from the confluence of the

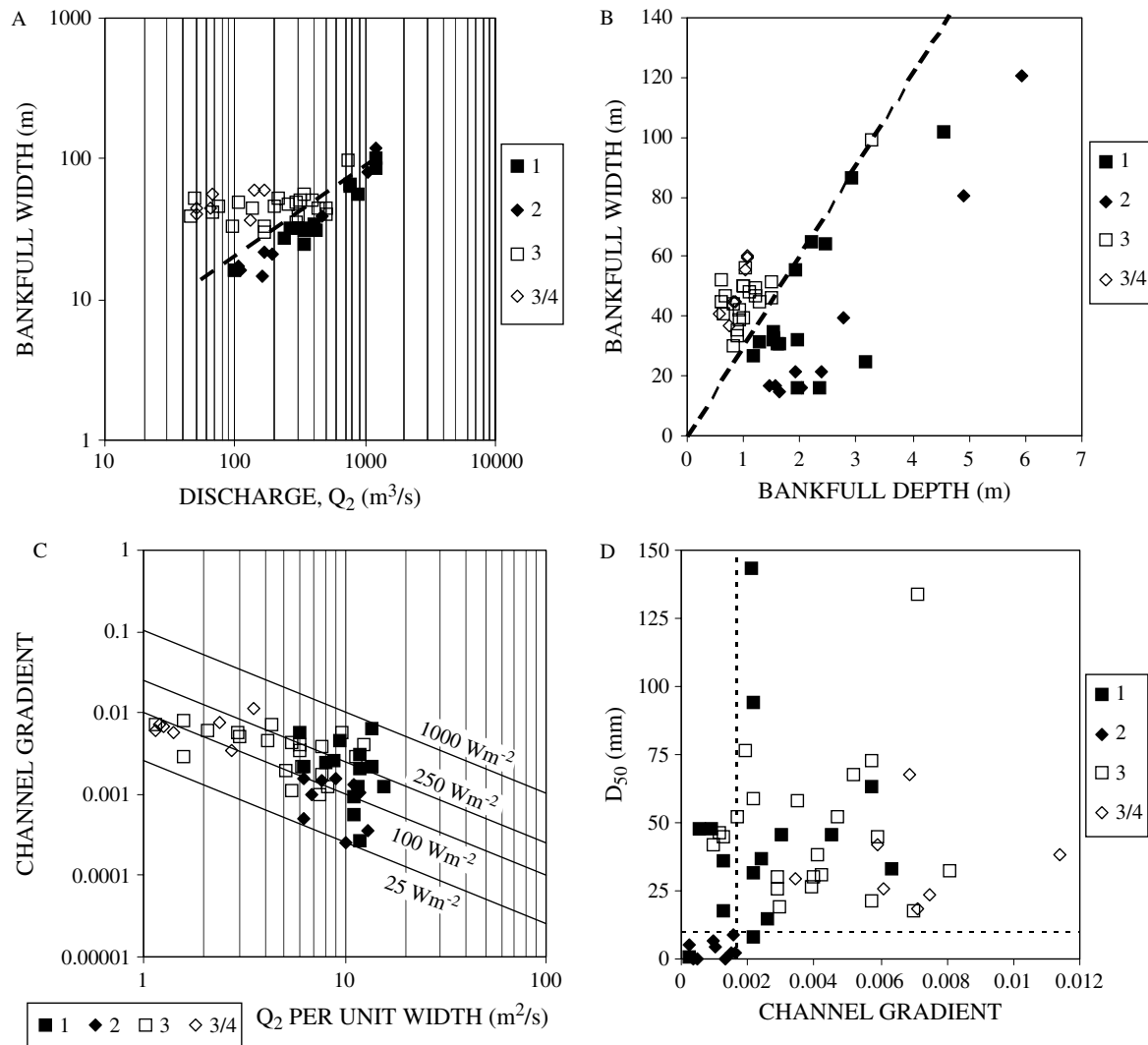


Figure 3. Main morphological, hydraulic and sedimentary characteristics of the 53 selected sites. (A) Bankfull width as function of biennial discharge. (B) Bankfull depth as function of bankfull width. The hatched line indicates a width-to-depth ratio of 30. (C) Channel gradient as a function of biennial discharge per unit width, with lines of given values of unit stream power. (D) Median diameter of sediments as a function of channel gradient. The vertical hatched line corresponds to a channel gradient of 0.00165; the horizontal hatched line corresponds to a D_{50} of 10 mm. Present channel morphologies: (1) sinuous; (2) meandering; (3) sinuous with alternate bars; (3–4) sinuous with alternate bars—locally braided

Sieve River), where values of incision range from 4 up to 9 m. Along the upper reach of the Sieve and Arno Rivers, incision still exceeds 2 m on average. Along the rivers of the southern part of the region (Cecina River, Cornia River, Ombrone River and its tributaries, Albegna River), incision appears to be generally moderate (except for some reaches in the Ombrone river system). Evidence of reaches where aggradation occurred are very uncommon, except for local situations. The regional distribution of vertical adjustments shown in Figure 4 does not reveal evidence of the types of spatial trend. The spatial distribution of vertical changes appears to be mostly controlled by the presence of bedrock gorges, where incision is generally reduced, alternating with alluvial reaches, where incision appears to be more pronounced. All the rivers studied are channelized in their terminal reach before flowing into the Tyrrhenian Sea and show a limited or absence of incision, due to the proximity of the base level.

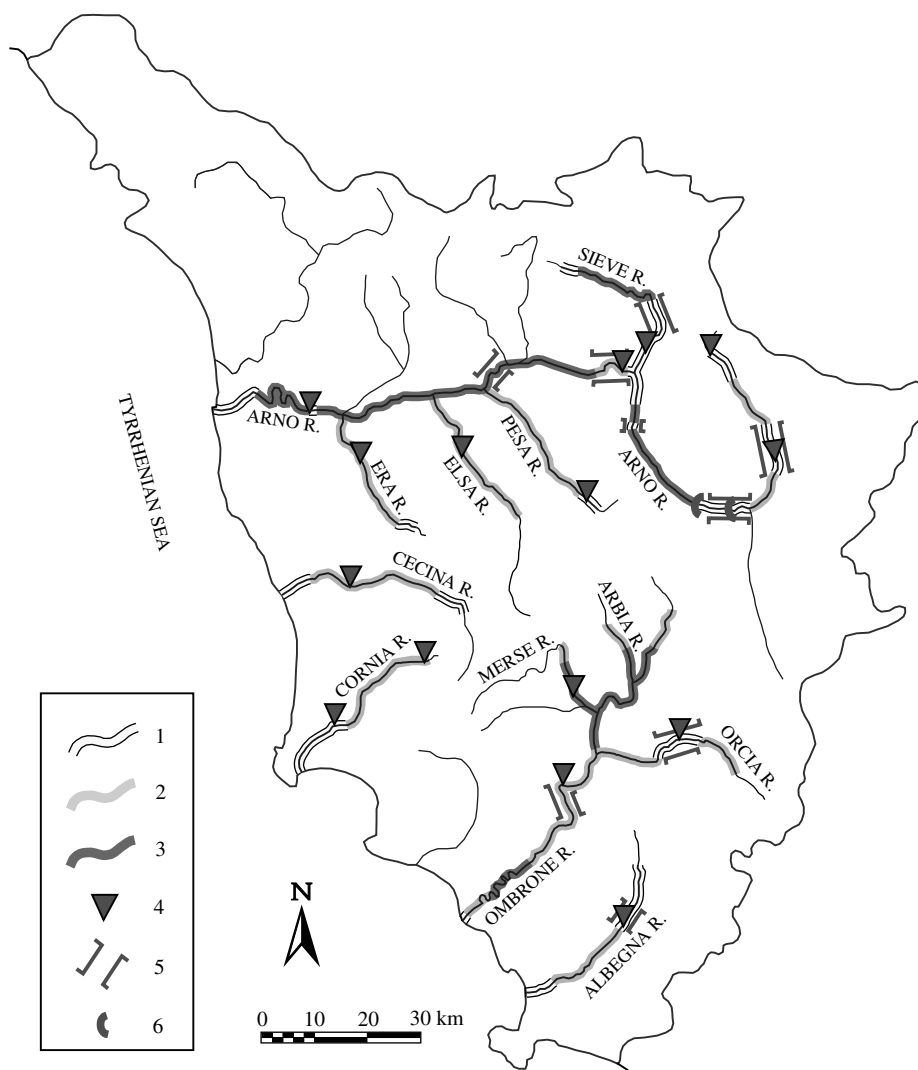


Figure 4. Schematic map of the bed-level lowering in the fluvial systems of Tuscany. (1) Absent or limited incision; (2) moderate incision (less than 2 m); (3) intense incision (more than 2 m); (4) gauging stations with specific gauge analysis conducted; (5) reaches with valley constriction (gorges) and bedrock thresholds; (6) dams (along the upper course of the Arno River)

Information regarding the temporal trend of bed-level adjustments is available for many cross-sections of the Arno River (Rinaldi *et al.*, 1997; Rinaldi and Simon, 1998) and for some of the gauging stations analysed. The two best examples were selected (Figure 5) where temporal trends of bed-level adjustments were available (from cross-section data or specific gauge analysis) and for which relatively long hydrological records were available, in order to investigate the possible changes in frequency and magnitude of floods and their possible control on vertical changes. The first example is relative to the reach of the Arno River (Lower Valdarno), characterized by the largest total incision of the region; for the second case, the river is characterized by a minor amount of incision, because it is a partially bedrock-controlled reach. As reported in previous studies (Rinaldi and Simon, 1998), two distinct phases of incision are distinguishable. A first minor degradational phase, occurring between the end of the 19th century and the first half of the 20th century and characterized by a limited bed lowering, has been interpreted as the result of extensive construction of weirs along tributaries and reforestation, which produced a decrease in bed-load supply to the fluvial system. This

phase was followed by an abrupt acceleration of degradation, starting from the period 1945–60 and extending to the beginning of the 1980s, with a significantly higher total incision.

Hydrological data (annual peak flows) has only been available starting from the 1920s and so they are not sufficient for investigating possible climatic controls on the first minor degradational phase, and little evidence of significant changes in magnitude or frequency of floods can be observed to explain the acceleration of channel incision observed in the second half of the 20th century. On the contrary, this period exactly coincides with the large increase in sediment mining after World War II. In the case of the Arno River, the construction of two dams along the upper course in 1957 contributed to an increase in the amount of incision. The temporal relation of this second type of disturbance with the trend of adjustments is particularly evident in the case reported in Figure 5B. The flood of 1966, the largest event at the regional scale during the period investigated, occurred when the degradational phase had already started, and does not seem to have had a direct influence on the trend of adjustment.

The second dominant type of adjustment identified on most of the rivers in the region is the narrowing of the active (bankfull) channel. Figure 6 clearly shows this type of change for two representative sites, for which the reduction of channel width is drastic as it is accompanied by a change in channel pattern that occurred between 1954 and 1993 (from sinuous with alternate bars to sinuous in the first example; from braided to sinuous with alternate bars in the second one). As noted previously, in spite of the limitations and relatively high margins of error in the measurements conducted on the aerial photographs, a large number of the sites analysed (29 out of a total of 42) show a certain reduction in channel width in the period from 1954 to 1993–98 (Figure 7A and B). As for the changes in bed elevation, measurements of channel width were

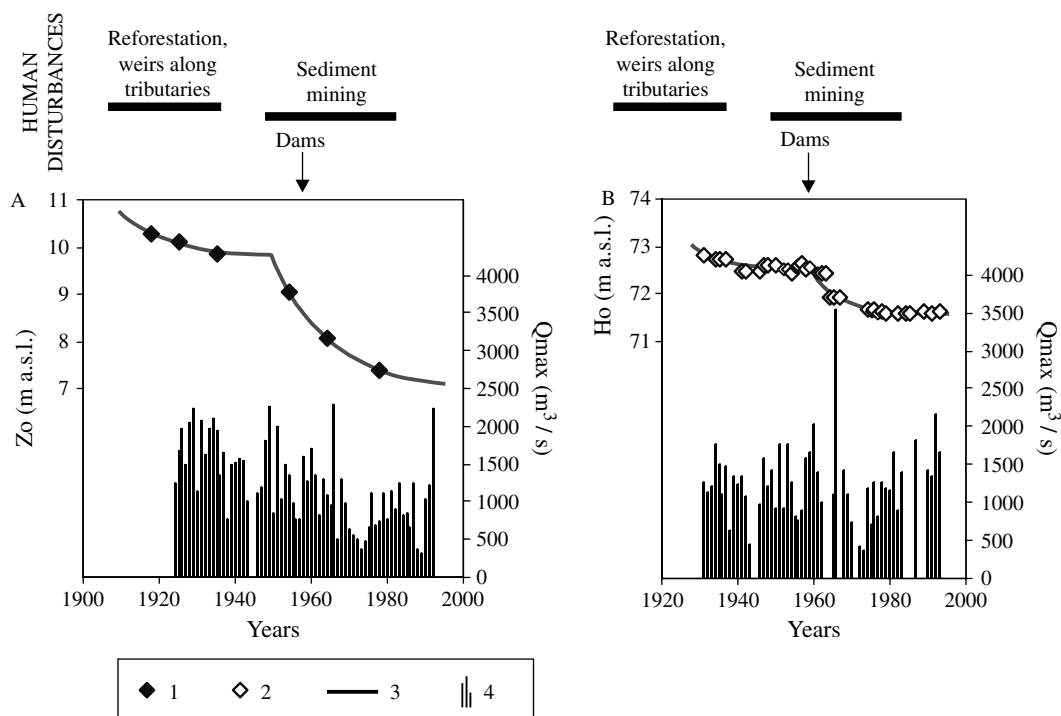


Figure 5. Trends of bed-level adjustments and flood record for two reaches of the Arno River. (A) The Arno River in the lower course. Hydrological data refer to gauging station 1 in Figure 1B, and the trend of bed-level elevation has been obtained by cross-section data at a site 12 km upstream. (B) The Arno River in the middle course, downstream from the confluence of Sieve River (gauging station 4 in Figure 1B). The trend of bed-level adjustments has been obtained by specific gauge analysis. (1) Bed-elevation Z_0 by cross-section data; (2) river stage associated with the mean of annual minimum discharges H_0 ; (3) trend of bed-level adjustments; (4) annual peak flow Q_{max} (data for 1944 and 1945 are missing). Human disturbances: horizontal bars indicate the period of maximum human activity; the arrow indicates the year (1957) of construction of the two dams in the upper course of the Arno River

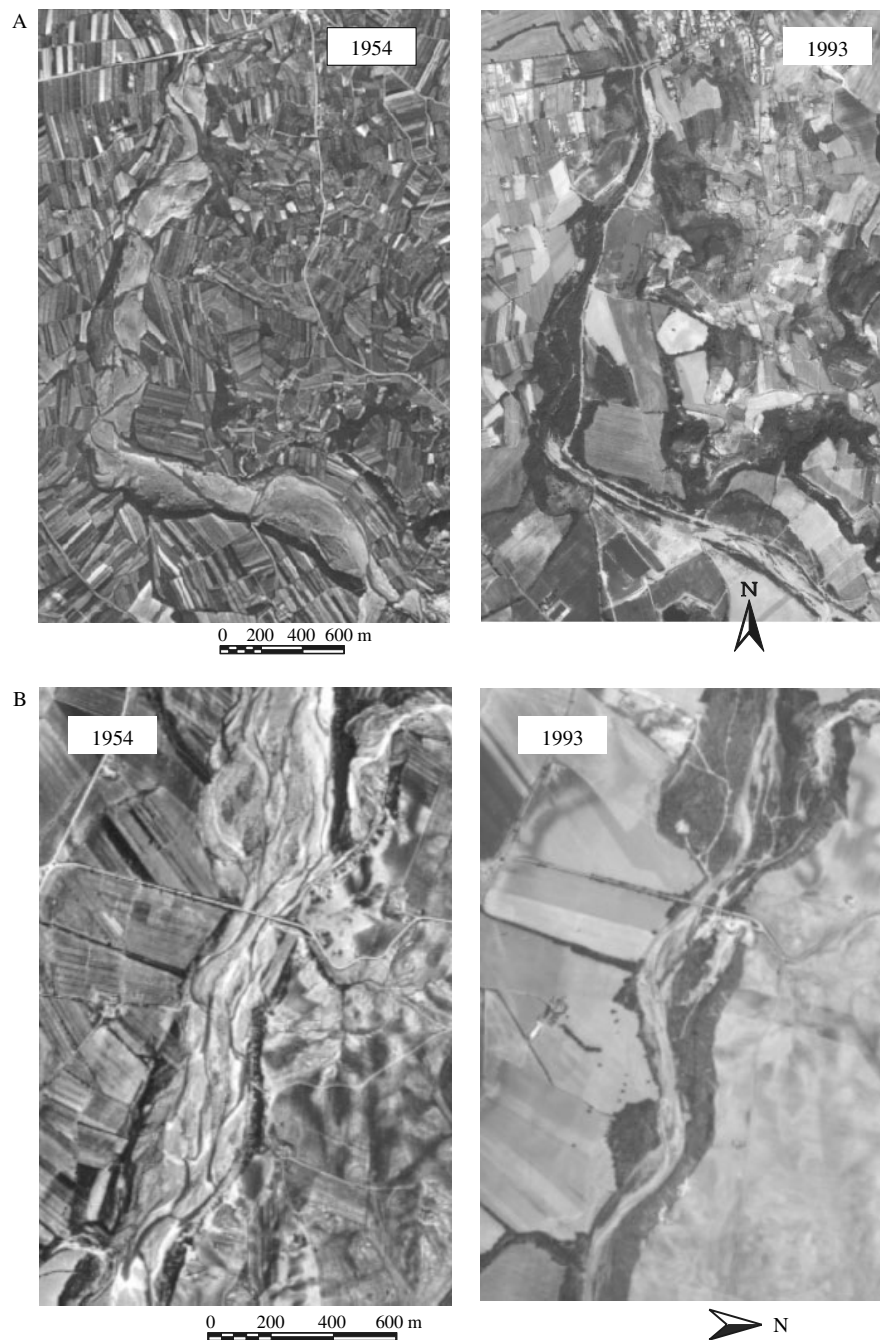


Figure 6. Examples of aerial photographs comparison. (A) Era River (site 7), 15 July 1954 and 2 September 1993; (B) Orcia River (site 43), 29 July 1954 and 30 August 1993 (aerial photographs for 1954: Istituto Geografico Militare, Authorization No. 5280 of 15 November 2000, reproduced by permission)

then used to classify the total changes. Classes of vertical and width adjustment and channel morphology for each of the 53 sites are summarized in Table II.

Measurements that resulted in a difference in channel width lower than the estimated margins of error were included in class A, containing limited and/or uncertain changes. Based on the percentage of reduction,

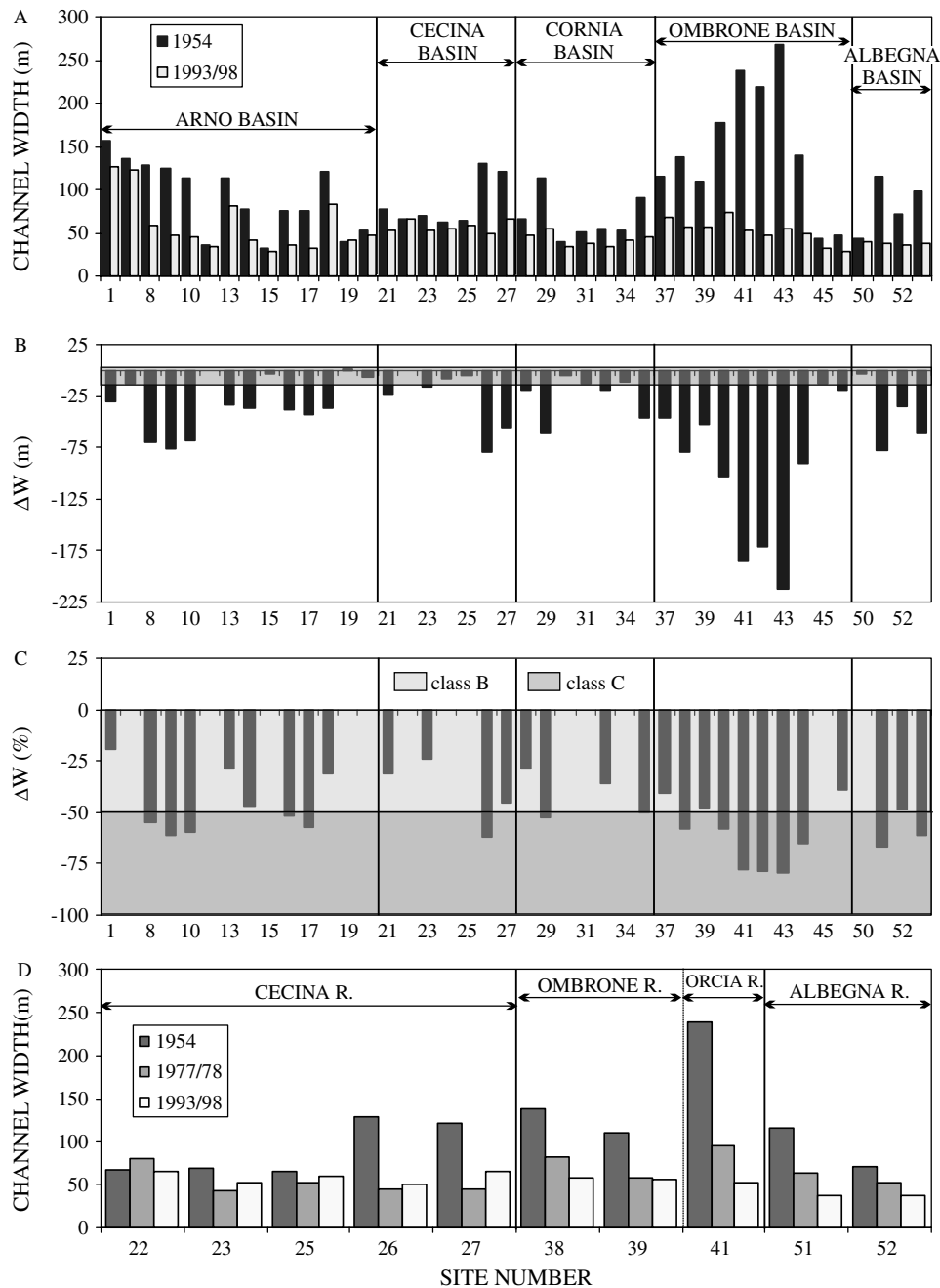


Figure 7. Changes of bankfull channel width measured from comparison of aerial photographs. (A) Comparison of bankfull width of 1954 and 1993–98. (B) Differences in bankfull width between 1993–98 and 1954 (negative values indicate narrowing). (C) Differences in bankfull width between 1993–98 and 1954 expressed as a percentage of the initial value (1954; negative values indicate narrowing). (D) Comparison of bankfull width for sites with available orthophoto maps of 1977–78

class B includes moderate changes, up to the 50% of the initial (1954) width, and class C includes sites with intense channel narrowing, above 50% of the initial width. None of the sites displayed a significant increase in channel width. A total of 13 sites (31% of the total) are included in class B, and 16 (38%) are in class C (Figure 7C).

Table II. Channel morphology, vertical and width adjustments (locations of the river reaches are shown in Figure 1C)^a

River reach	MO ^a	VA ^b	WA ^c	River reach	MO ^a	VA ^b	WA ^c	River reach	MO ^a	VA ^b	WA ^c
1	M	IN	B (−19.2%)	19	S a.b.	MO	A	37	(B) S a.b./B	L/A	B (−40.4%)
2	S	IN	A	20	S a.b.	MO	A	38	(S a.b.) S	MO	C (−58.3%)
3	M	MO		21	S a.b.	MO	B (−30.9%)	39	(S a.b.) S	MO	B (−48.1%)
4	M	MO		22	S a.b.	MO	A	40	(S a.b.) S	MO	C (−58.2%)
5	M	L/A		23	S a.b.	MO	B (−24.3%)	41	S a.b.	MO	C (−78%)
6	M	MO		24	S a.b.	L/A	A	42	S a.b.	MO	C (−78.4%)
7	(S a.b.) S	MO		25	S a.b.	MO	A	43	(B) S a.b.	MO	C (−79.7%)
8	(B) S a.b./B	L/A	C (−54.8%)	26	S a.b.	MO	C (−61.7%)	44	(B) S a.b./B	MO	C (−65.0%)
9	S a.b.	MO	C (−61.4%)	27	S a.b./B	L/A	B (−45.6%)	45	S	IN	A
10	S a.b.	MO	C (−59.9%)	28	S a.b.	MO	B (−28.7%)	46	S	MO	B (−39.3%)
11	M	MO		29	S a.b.	MO	C (−52.4%)	47	S	IN	
12	S a.b.	MO	A	30	S a.b.	MO	A	48	M	IN	
13	S	MO	B (−28.9%)	31	S a.b.	MO	A	49	M	MO	
14	S	MO	B (−46.8%)	32	S a.b.	MO	B (−36.0%)	50	S	MO	A
15	S	IN	A	33	S	IN		51	S a.b.	MO	C (−67.0%)
16	(S a.b.) S	MO	C (−51.8%)	34	S a.b./B	MO	A	52	S a.b.	MO	B (−48.4%)
17	(S a.b.) S	IN	C (−57.6%)	35	S a.b./B	MO	C (−50.3%)	53	(B) S a.b./B	L/A	C (−61.4%)
18	S a.b.	IN	B (−31.0%)	36	M	MO					

^a MO: present morphology (the initial channel pattern of 1954 is indicated in parentheses, in case a change has occurred in the meantime). M: meandering; S: sinuous; S a.b.: sinuous with alternate bars; B: braided.

^b VA: vertical adjustments. L/A: limited or absent incision (locally aggradation); MO: moderate incision; IN: intense incision.

^c WA: width adjustments. A: Limited and/or uncertain changes; B: moderate narrowing; C: intense narrowing; ΔW: change in bankfull width measured from comparison of aerial photographs of 1954 and 1993–98.

Comparison with orthophoto maps of 1977–78 permitted verification of the date of narrowing for ten sites (Figure 7D). A dominant trend is not observed for the ten available sites. For three of them, relative to the Cecina River (sites 22, 23, and 25), channel width changes are not significant between 1954 and 1978, nor from 1954 to 1993. For the other two sites along the same river (sites 26 and 27), an initial drastic narrowing (between 1954 and 1978) was followed, more recently, by a slight channel widening. For four of the remaining sites (38, 39, 41, and 51), most of the channel narrowing occurred from 1954 to 1977, and in just one case (site 52) the channel width in 1977 was intermediate between the measures from 1954 and 1998.

The effects of vertical and width adjustments are evident in the morphology of the incised channels. It has to be noted that, although narrowing represents the type of width adjustment affecting the active channel, the overall cross-section is, in all the cases, subject to some amount of widening, as a consequence of the progressive retreat of the terrace scarps by bank failures. The form of the incised channels is better described by considering the channel geometry at the scale of the whole cross-section, and comparing it with the bankfull channel. In Figure 8, the difference in depth is reported as a function of the difference in width between the whole cross-section and the bankfull channel for incised reaches of the different channel morphologies. The figure shows that in sinuous–meandering channels the difference in width is generally limited (the lower terrace scarps are adjacent to the bankfull channel), whereas the difference in depth is remarkable, as a consequence of higher incision. In contrast, sinuous with alternate bars–locally braided channels often present more significant differences in width (bankfull channel contained in a much larger whole cross-section delimited by the lower terrace scarps) and more limited differences in depth.

Subsequently, in the 42 sites where the channel width was measured, a comparison with the amount of vertical changes that occurred in the same reaches was carried out, illustrating the number of cases for each combination of vertical and width adjustments (Figure 9). Many of the sites fall into the class of moderate incision, and the associated changes in width are variable for this class, with the majority belonging to the category of intense narrowing. Although sites falling into the category of intense incision are relatively few,

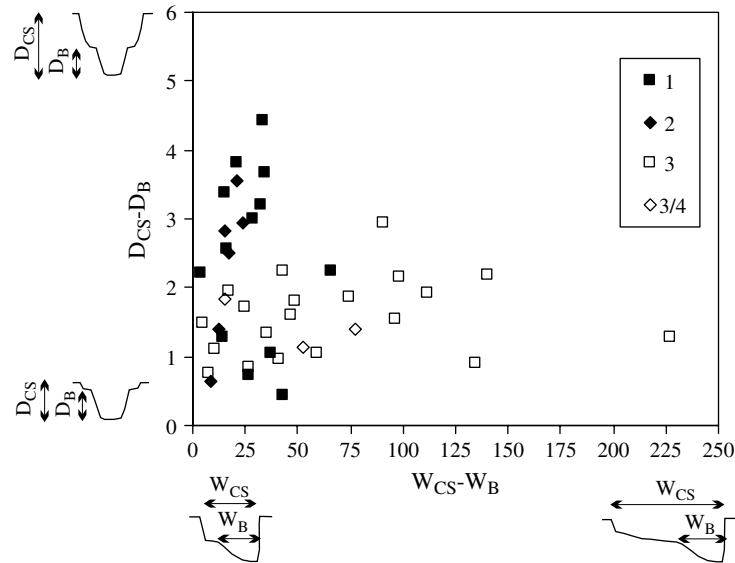


Figure 8. Morphological characteristics of the whole cross-section in relation to the bankfull channel. W_{CS} : whole cross-section width; W_B : bankfull width; D_{CS} : whole cross-section mean depth; D_B : bankfull mean depth. (1) Sinuous; (2) meandering; (3) sinuous with alternate bars; (3-4) sinuous with alternate bars locally braided

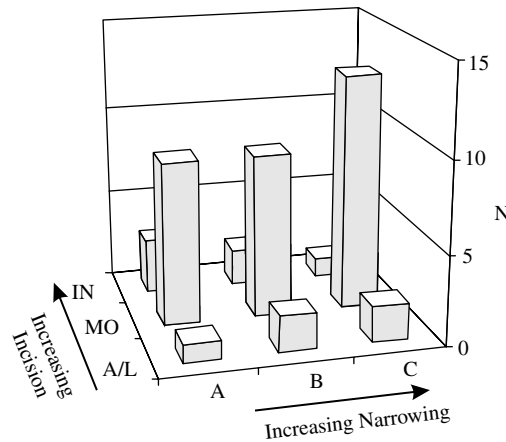


Figure 9. Relations between vertical, lateral adjustments, and channel morphologies. Vertical adjustments: A/L = absent or limited incision; MO = moderate incision; IN = intense incision. Bankfull width changes ΔW : A = limited or uncertain changes; B = moderate narrowing ($\Delta W < 50\%$); C = intense narrowing ($\Delta W > 50\%$). N : number of cases

it is evident that the number of cases with associated intense narrowing is still smaller. Therefore, these data suggest that rivers with high incision are not associated with high amounts of narrowing, the latter being generally related to moderate incision. This is in contrast to the direct relation between vertical and width adjustments observed by Liebault and Piegay (2001) on the Roubion River. This is clearly related to the differences in initial channel morphology of the rivers. In fact, in this study it was found that those rivers that were originally sinuous with alternate bars to braided were generally affected by moderate incision and moderate to intense narrowing; then again, sinuous–meandering channels mainly adjusted vertically, with only slight narrowing.

DISCUSSION

Channel incision and narrowing: causes

The results obtained show that drastic, rapid and widespread channel adjustments have occurred along the main alluvial rivers of Tuscany during the last 50 years.

Previous studies conducted on the Arno River (Billi and Rinaldi, 1997; Rinaldi *et al.*, 1997; Rinaldi and Simon, 1998) have agreed in pointing out human disturbances (construction of weirs along tributaries and reforestation, sediment mining, dams) as the main causes of channel incision. Recent studies concentrated on British rivers (Macklin and Lewin, 1989; Rumsby and Macklin, 1994) have demonstrated the important role of climatic changes and related variations in flood frequency and magnitude as a regional mechanism in determining channel instability. In such catchments with a long history of human disturbances, as in Tuscany, it is very difficult, however, to distinguish between natural and human-induced causes of channel instability. As regards the 20th century, although few hydrological data are available to test possible changes in flood magnitude or frequency, the effectiveness of natural factors seems very limited compared with the high human impact. From 1950 to 1980 the Arno River bed degraded about as much as during the previous 100 years (1850–1949), i.e. in those three decades the stream bed adjusted at a rate three times greater than in the previous century (Billi and Rinaldi, 1997). No evidence of hydrologic or climatic changes exists to justify such an abrupt acceleration of channel incision, whereas the period 1950–80 coincides exactly with the large increase in sediment mining because of the post-World War II reconstruction and the economic development of the region.

Apart from bed incision, active channel narrowing is the second main type of channel adjustment observed for most of the sites selected in this study. This combination of adjustments has recently been observed for other European rivers (Gurnell, 1995; Marston *et al.*, 1995; Surian, 1999; Winterbottom, 2000; Liebault and Piegay, 2001).

Incision is well explained, following the classical scheme of Lane (1955), by an excess of stream energy (or power) in relation to the sediment discharge, as a consequence of a decrease in the volume of sediment delivered from tributaries (from sediment trapping behind weirs and reforestation) and of a drastic reduction of in-stream sediment by mining activity. However, the scheme of Lane (1955) does not explicitly allow for complex responses (Schumm, 1977; Shields and Doyle, 2000) and is not well suited to the interpretation of width adjustments. To explain channel narrowing, it is more convenient to refer to the scheme of Schumm (1977), who suggested that a decrease in bedload may induce a decrease in channel width, meander wavelength and gradient and/or an increase in depth and sinuosity. Therefore, a possible cause of channel narrowing in a disturbed alluvial river is a reduction in bedload while discharge remains constant, with abandoned bedforms that become progressively stabilized (Schumm, 1977).

Narrowing frequently occurs in combination with bed incision, and may also be explained as a direct consequence of bed-level lowering, due to flow concentration in a narrower cross-section and progressive colonization of formerly active portions of the channel bed by vegetation (Marston *et al.*, 1995; Bravard *et al.*, 1999; Tsujimoto, 1999). Vegetation commonly has an important role in channel narrowing by contributing to increased sediment deposition and bank stability (Schumm and Lichty, 1963; Williams and Wolman, 1984; Friedman *et al.*, 1996).

In the case of narrowing associated with bed incision, channel evolution is complex and the reciprocal role of bed and width adjustments is not yet well understood. In fact, incision and narrowing may induce opposite tendencies in stream energy, since the dominant effect of incision is normally to reduce channel gradient, whereas narrowing induces an increase in shear stress and, therefore, in stream energy. Consequently, channel narrowing may provide positive feedback (Bravard *et al.*, 1999), inducing further degradation and/or a partial recovery of channel width, and the final channel configuration will be the result of a compromise of these two opposite tendencies.

In this study, channel narrowing occurred in combination with incision for most of the cases. In fact, of a total of 42 sites, only in four cases did channel narrowing occur while incision was absent or limited. Channel narrowing may be interpreted as a consequence of bed-level lowering and of the general reduction of bed-load supply and in-channel sediment availability caused by human activities. However, contrary to the

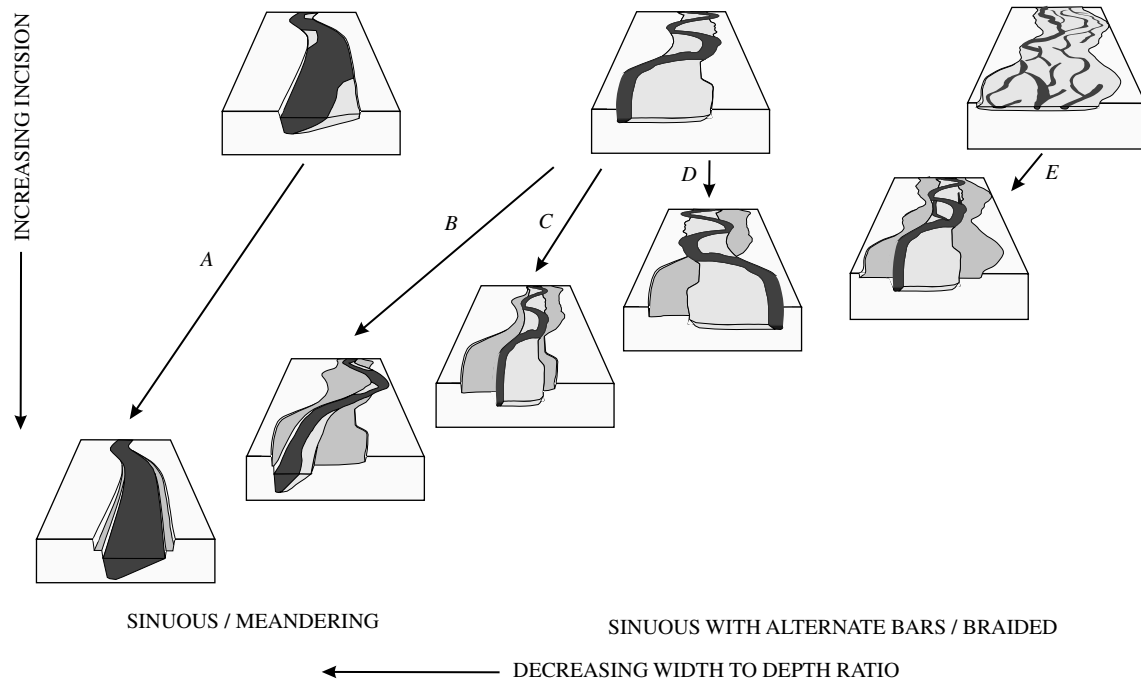


Figure 10. Sketch of the main planform changes as a function of incision and initial channel morphology. In black: low-water channel; in lighter grey: active bars; in darker grey: new or incipient floodplain deriving from abandonment of previous active bars after incision

results of other studies (Liebault and Piegay, 2001), it has been shown that the amount of narrowing is not in direct relation to the total lowering of the bed level.

Styles of channel adjustment

The results of the analyses and numerous observations of aerial photographs and in the field suggest different styles of channel evolution and relative amounts of vertical and width adjustments, mainly depending on initial channel morphology, as summarized in Figures 10 and 11. In particular, Figure 10 focuses on planimetric changes and Figure 11 illustrates vertical changes and the evolution of geomorphic surfaces (active bars and floodplain). The sketch reported in Figures 10 and 11 represents a regional classification scheme based on adjustment processes and trends of channel changes, starting from a basic distinction in the main morphological types.

Initial channel morphologies refer to the period prior to the main phase of incision, that occurred from the 1950s to the 1980s, as a result of intense sediment mining, in addition to the general reduction in sediment supply started during the previous decades.

Initially sinuous–meandering rivers mostly adjusted through intense incision and a small amount of narrowing (A). Conversely, for initially sinuous with alternate bars and braided channel morphologies, limited bed lowering was sufficient to cause the abandonment of the active channel bars and the creation of a new incised channel at a lower level. In particular, for sinuous channels with alternate bars, three main final morphologies can be distinguished, depending on the amount of incision. In some cases (D) the river adjusted by slight incision and narrowing, shifting laterally and maintaining approximately the same original morphology. In several other cases (C), slightly higher levels of incision caused large portions of active bars to be abandoned and, subsequently colonized and stabilized by vegetation. The final channel pattern remained the same, but intensely narrowed. In still other cases (B), channel incision caused such a drastic narrowing and reduction or disappearance of active bars that the channel changed to a sinuous morphology. For initially braided channels (E), a limited amount of incision was sufficient to cause an intense narrowing and a change

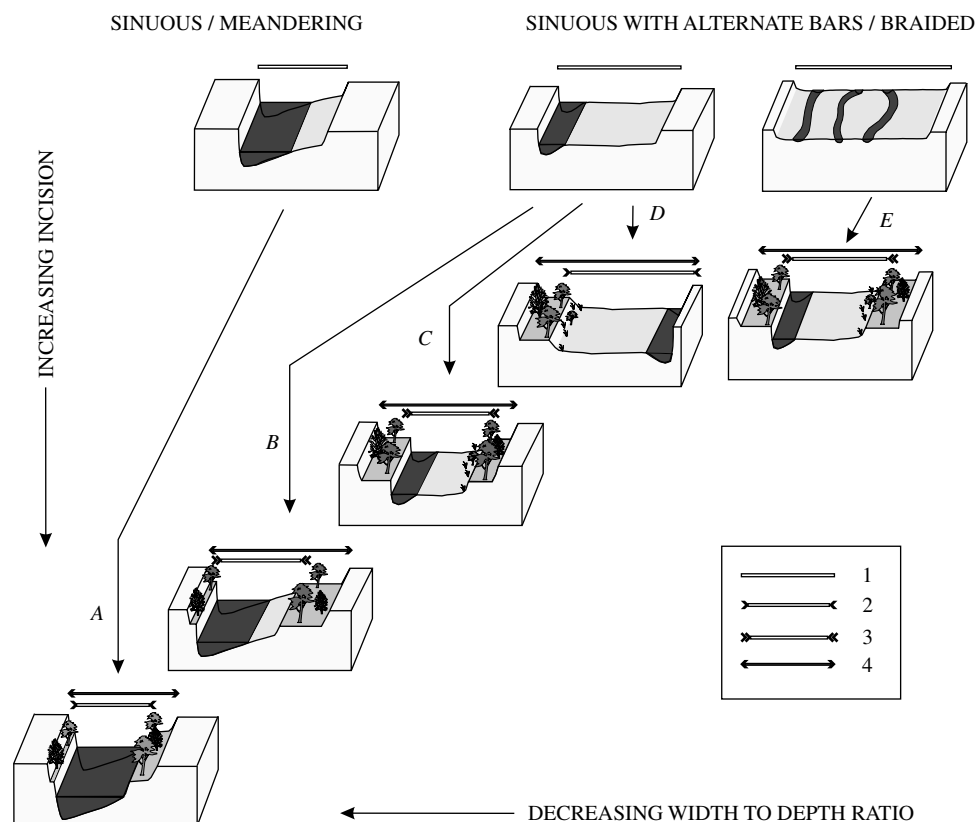


Figure 11. Sketch of the cross-section adjustments and development of vegetated surfaces as a function of incision and initial channel morphology. (1) Initial bankfull width; (2) moderate bankfull channel narrowing; (3) intense bankfull channel narrowing; (4) changes in the whole cross-section width. In black: low-water channel; in lighter grey: active bars; in darker grey: new or incipient floodplain deriving from abandonment of previous active bars after incision

in river morphology from multi-thread to a single-thread sinuous channel with alternate bars, in some cases with local braiding phenomena.

In Figure 11 the changes in channel width for both the active (bankfull) channel and the whole cross-section (delimited by the terrace scarps formed following the bed-level lowering) are illustrated schematically. Bankfull width decreases in all cases, whereas surfaces that can be described as new or incipient floodplains were mainly generated by the abandonment, and subsequent colonization by vegetation, of previously active gravel bars during or following the phase of incision. In all cases, the progressive retreat of the terrace has caused a widening of the overall cross-section.

Differences with other fluvial systems

The scheme of channel adjustments that has occurred in Tuscan fluvial systems presents some significant differences from channel evolution models (CEMs) originally proposed for incised rivers in loess-derived alluvium in the southeastern USA (Mississippi, Tennessee) (Schumm *et al.*, 1984; Simon and Hupp, 1986; Watson *et al.*, 1986; Simon, 1989). These models are based on the concept of location-for-time substitution and on shifts in dominant adjustment processes, and describe a phase of initial bed incision, followed by bank instability and widening, and by a subsequent stage of downstream aggradation as degradation migrates upstream. The six-stage model has also been applied to the loess area of the midwestern USA (Simon *et al.*, 1996; Simon and Rinaldi, 2000), both for silt-bed and sand-bed streams, and the same sequence of degradation and aggradation was also observed for coarse-grained streams of the Toutle River system (Simon and Thorne, 1996). Similar geomorphic evolution and trends have been described for the contemporary arroyos that formed

in the late 19th and early 20th centuries in many regions of the southwestern USA (Elliott *et al.*, 1999). A seven-stage evolution model has been proposed (Elliott, 1979; Gellis, 1988), where arroyo evolution involves a sequence of channel deepening, widening, and inner floodplain formation.

Differences in the channel adjustments of the Arno River compared with other unstable fluvial systems had already been observed in a previous study on bed-level adjustments of the river (Rinaldi and Simon, 1998).

The main differences observed between fluvial systems of USA and rivers included in this study are the following: (a) the lack of an aggradational phase and of a spatial distribution of dominant processes and trends; (b) channel narrowing rather than widening. The main factors that can be considered significant for explaining these differences are: (a) geological bed controls; (b) different types of human disturbance; (c) channel morphologies and the characteristics of bed and bank materials.

As regards the geological control, an important factor in channel evolution for regions of the USA, where CEMs were developed, was the general lack of rock or other resistant materials in stream beds, so that incision was able to migrate upstream in the fluvial system (Thorne, 1999). Conversely, the presence in the study area of bedrock-controlled reaches alternating with alluvial reaches has prevented the upstream migration of bed degradation and the consequent dynamic response in the fluvial systems.

The different types of human disturbance appear to be a dominant factor. In the case of Tuscan rivers, sediment mining can be considered as the dominant type of disturbance during the 20th century for triggering or accelerating bed incision. Many studies have described the geomorphic effects of in-stream sediment mining on alluvial rivers (e.g. Collins and Dunne, 1989, 1990; Kondolf, 1994; Sear and Archer, 1998). The first response to gravel mining is upstream migrating bed incision, caused by the alteration of the bed profile by pits and knickpoint migration; however, pit excavation can also induce incision downstream, as a consequence of the sediment load trapped in the pits and the resulting excess of energy downstream (Kondolf, 1994).

In the case of Tuscan rivers, although estimates of extracted volumes of sediments are not available, sediment mining has been extensively and simultaneously carried out at many points along the main alluvial channels and tributaries of the fluvial systems. Incision at the points of extraction is a direct result of sediment mining *in situ*, whereas upstream and downstream migrating effects produced bed degradation along the reaches between the pits. The adjustments occurred mostly in synchronism longitudinally along the rivers affected by mining, rather than by a dynamic response migrating along the fluvial system.

The overall effect of such extensive sediment mining was a net decrease of the volume of sediment available in the fluvial systems, as opposed to CEMs, where upstream migrating degradation and subsequent widening by bank failures produce additional sediment available for downstream aggradation. In this case, bed-level lowering did not produce new volumes of available sediment, but was rather the result of sediment extraction from the system. Furthermore, the lack of widening is another factor that controls the substantial absence of available sediment for aggradation in the downstream reaches of the Tuscan fluvial systems, and this, combined with geological bed controls, limits the spatial distribution of channel processes.

Channel narrowing, rather than widening, represents another significant difference from CEMs. This type of adjustment has recently been described for many mountain and piedmont rivers of southeastern France (Marston *et al.*, 1995; Liebault and Piegay, 2001, 2002), where it has been interpreted to be the result of various causes, including sediment supply decrease due to deforestation, effects of major floods, the stabilizing role of riparian vegetation root systems due to forest development on river margins, and human abandonment of intensive floodplain land use. In the cases studied, the lack of widening, rather than being related to the bank material, appears to be controlled primarily by the reduced bed-load supply and transport, caused by human disturbance, the consequent confinement of an incised active channel and the colonization of vegetation on abandoned active bars. An additional factor for absence of widening, along rivers with higher human control (the Arno River and some of its tributaries), notwithstanding intense incision and predominantly cohesive banks, is the presence of bank stabilization measures preventing channel widening.

The end of sediment mining activity, dated around the middle of the 1980s, has probably started a slow recovery phase of channel morphology. Active bank retreat along many unprotected reaches has started to deliver new volumes of sediments, although presently there is no consistent evidence of bed-level changes and the channel width is generally still significantly lower than before the channel adjustments.

SUMMARY AND CONCLUSIONS

All the main alluvial rivers of the region have been subjected to intense channel adjustments during the 20th century. Human disturbances appear to be the dominant factors of adjustments: a significant acceleration of channel incision occurred during the period 1945–80, in concomitance with the maximum sediment mining activity at a regional scale. Other human disturbances contributing to channel instability have been: (a) reduction in sediment supply due to construction of weirs along tributaries and because of reforestation; (b) for the Arno River, construction of dams in the upper course. Available data and field evidence suggest that incision is generalized along all the fluvial systems investigated. The highest rates of bed-level lowering (up to 9 m) are observed along the Arno River, whereas rivers of the southern part of the region experienced a significantly minor amount of incision. Regional distribution of vertical adjustments does not show clear spatial trends, since upstream migration has often been prevented by the presence of bedrock gorges.

Channel narrowing represents a second major type of adjustment, and occurred simultaneously or following bed-level lowering along most of the reaches analysed. Some 13 sites (31% of the total) have been subjected to a reduction in channel width up to the 50% of the initial value, whereas for 16 sites (38% of the total) the reduction was higher than 50% of the initial value.

Results deriving from estimations of vertical and width adjustment and observations by aerial photographs and in the field are summarized in a regional scheme of channel evolution. Different styles of channel adjustment are described, mainly depending on the initial channel morphology. Rivers that were originally sinuous with alternate bars to braided generally adjusted by a moderate incision and a moderate to intense narrowing, whereas sinuous–meandering channels mainly adjusted vertically, with a minor amount of narrowing.

Channel adjustments occurring along the rivers of Tuscany present some differences compared with CEMs proposed in the literature for incised fluvial systems in loess-derived alluvium in the southeastern USA. The main differences are: (a) the lack of aggradational phases and of spatial distribution of dominant processes and trends; (b) channel narrowing rather than widening. These differences are explained by the following main factors: (a) geological bed controls; (b) different types of human disturbance; (c) channel morphologies. In particular, sediment mining has been a dominant factor, being carried out extensively along most of the main alluvial rivers of the region. The net decrease in volumes of available sediments for bed load, combined with the reduced sediment supply from the basin and to the absence of widening, caused a net deficit of sediments in the fluvial systems and a lack of an aggradational phase in the downstream river reaches. Channel narrowing is explained by the general reduction of bed-load supply and in-channel sediment availability due to the human disturbances, and the indirect consequence of incision, with the abandonment, and successive colonization by vegetation, of large portions of active bars.

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